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Nonlinear Flatness Control Applied to Supercapacitors Contribution in Hybrid Power Systems using Photovoltaic Source and Batteries

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Abstract

For a stand-alone application, and to demonstrate role of supercapacitors as a transient power source, a nonlinear control strategy based on the flatness approach is applied to manage energy flows in two systems: the first includes a photovoltaic (PV) source considered as a main source and lead-acid batteries used as storage unit; the second is obtained with the hybridization of the PV source, lead-acid batteries, and supercapacitors.

The simulation results are presented and discussed when applying different solar illuminations and consumption profiles.

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Keywords: Photovoltaic source; Battery; supercapacitor; hybridization; energy management; flatness control

1. Introduction

The Photovoltaic production is a renewable energy that can be produced when it is consumed, and is highly dependent on weather conditions. Therefore, it should be stored during the day [1]. Presently, the lead battery is the most common electrochemical storage technology. Her use has been widely demonstrated, but, costs and life-cycle characteristics are not yet satisfactory and need to be improved for stand-alone applications [2]. Developed at the end of the seventies for signal applications (example: for memory back-up), a supercapacitor presents a capacitance of some farads and specific energy of about 0.5 Wh.kg⁻¹. The power supercapacitor appeared during the nineties and

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brought components of thousands of farads and high specific power of several kW.kg^{-1} . When a lead-acid battery is subjected to extreme conditions (high discharge current, for example), her performances degrade rapidly. So, the use of a hybrid storage sources is indispensable: the battery will be dedicated to store and supply the daily produced photovoltaic energy, while the supercapacitor would deals with high solicitations (deep discharges) [3].

This paper presents a comparison between two hybrid sources used to supply a house load: "PV/Batteries" and "PV/Batteries/Supercapacitors". The energy management among different components is assured by applying a nonlinear control based on the flatness approach. The batteries final state of charge permits to demonstrate role of the supercapacitors as a transient power source.

2. Modelling of the autonomous hybrid systems

2.1. Photovoltaic source

A photovoltaic generator converts illumination into electric current. He is obtained by the combination of several cells to adapt the theoretical energy and the load demand. The energy supplied by a PV generator is written as follows [3-4]:

$$E_{PV} = n_e P_c \quad (1)$$

n_e : number of daily illumination hours [h/d]

P_c : Peak power [W]

An MPPT (Maximum Power Point Tracking) controller is used to allow operating the PV source under the maximum available power.

2.2. Lead-acid batteries

The electrical model of a lead-acid battery has an electromotive force (E_0) modelling the battery open circuit voltage, a capacitor (C_b) modelling the battery internal capacity, and an internal resistance (R_s) [5-6].

- The batteries voltage and state of charge are written as follows:

$$v_b = E_0 - v_{Cb} - R_s i_b \quad (2)$$

$$\text{SOC}_b = \left(1 - \frac{Q_{dB}}{C_B} \right) \times 100 \quad (3)$$

C_B : nominal capacity [Ah]

Q_{dB} : Quantity of charge missing comparing to C_B

2.3. Supercapacitors

The basic and commonly used equivalent model of a supercapacitor is a capacitor (C_{elem}) in series with a resistor (R_{elem}) [5] [7].

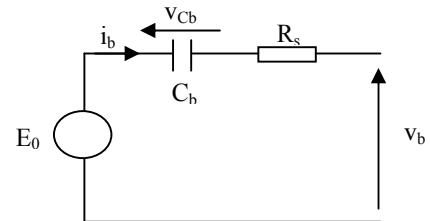


Fig. 1. R-C model of the lead-acid batteries.

- The supercapacitors voltage and state of charge are written as follows [5] [8]:

$$v_{sc} = v_{Csc} - R_{sc} i_{sc} \quad (4)$$

$$SOC_{sc} = \left(\frac{4}{3} \left(\frac{E_{sc}}{E_{scmax}} - \frac{1}{4} \right) \right) \times 100 \quad (5)$$

E_{sc} : stored energy [J]

E_{scmax} : maximal contained energy [J]

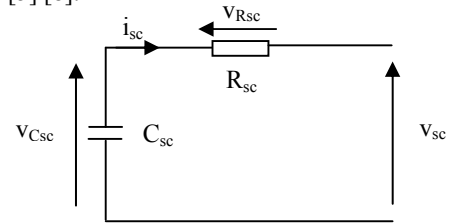


Fig. 2. Model of the supercapacitors.

2.4. Energy consumption

The energy balance of the chosen house is shown in Table 1.

Table 1. Daily consumption.

Load	Power [W]	Elements number	Use during [h/d]	Daily consumption [Wh/d]
Fluorescent	20	5	4	400
Refrigerator	70	1	10	700
Deep freeze	120	1	10	1200
TV	75	1	4	300
Washer	300	1	1	300
PC	40	1	4	160
Total				3060

2.5. Thresholds voltages

Different thresholds voltages for the hybrid storage unit "charging/discharging" are summarized in Table 2.

Table 2. Thresholds voltages.

Threshold	Definition	Value
V_1	High threshold for stop charging batteries	52V
V_2	Low threshold for stop discharging batteries	47.2V
V_3	High threshold for stop charging supercapacitors	30V
V_4	Low threshold for stop discharging supercapacitors	15V

3. Flatness control of the autonomous hybrid systems

3.1. System control

The flatness concept was proposed fifteen years ago [9] by Michel Fliess [1], and has been used in different applications of electrical engineering such as hybrid sources based on Fuel cell/Supercapacitors [10-13] and Batteries/Supercapacitors [14-15].

The major advantage of the flatness approach is to plan the desired trajectory of the flat output variable. If the modelling is without error, it is possible to know the evolution of all variables without having to solve any differential equation [10], simplifying, then, the system control.

3.2. Flatness demonstration

To demonstrate flatness of the two systems models, the DC link voltage and supercapacitors power are considered, respectively, as state and control variables. According to definitions cited in [16] and [17], models are «differentially flat». So, the capacitive energies can be controlled to their references given by:

$$y_{busref}(t) = \frac{1}{2} C_{bus} v_{busref}(t)^2 \quad (6)$$

Using the following law:

$$\begin{aligned} & (\dot{y}_{bus} - \dot{y}_{busref}) + k_{11}(y_{bus} - y_{busref}) + \\ & k_{12} \int_0^t (y_{bus} - y_{busref}) dt = 0 \end{aligned} \quad (7)$$

Consider:

$$\begin{cases} k_{11} = 2\xi w_n \\ k_{12} = W_n^2 \end{cases} \quad (8)$$

Where ξ and w_n represent, respectively, the desired damping coefficient and natural pulse.

3.3. Storage unit principle

The power management is based on:

- 1) Use of lead-acid batteries for:
 - Compensate the difference in power between load and the main source, and regulate the DC link voltage (first system).
 - Compensate the difference in power between load and the main source (second system).
- 2) Use of supercapacitors for:
 - Compensate the difference in power between load and main source and batteries (second system).
 - Provide and absorb the power needed to control the capacitive voltage (second system).

3.4. Structure of the first autonomous hybrid system

Structure of the system "PV/Batteries" is showed in figure 3.

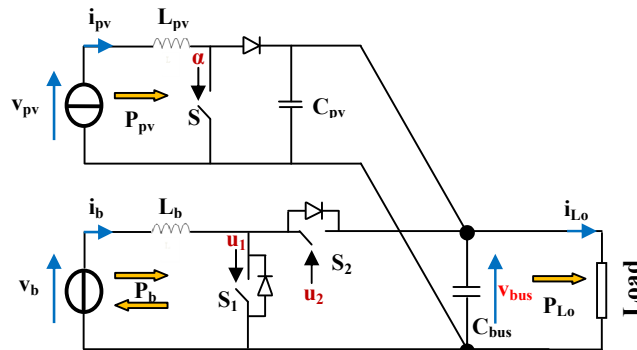


Fig. 3. Structure of the first hybrid system.

Different characteristics, obtained using the worst month, are summarized in Table 3.

Table 3. Characteristics of the first system.

PV source: AEG-40 is chosen			
Peak power [W]	Elements number	Surface [m ²]	
1920	50	19.2	
Lead-acid batteries: Yuasa NP65-12 is chosen			
Nominal voltage [V]	Rated capacity [Wh]	Depth of discharge [%]	Elements number
48	4707.7	60	20
Converters			
Inductance L _{pv} [H]	Inductance L _b [H]	Inductance L _{sc} [H]	Capacity C _{pv} [F]
0.0007	0.0015	0.03	0.0002
DC link			
Nominal voltage [V]		Capacity [F]	
24		0.025	

The simulation results are presented in the next figures.

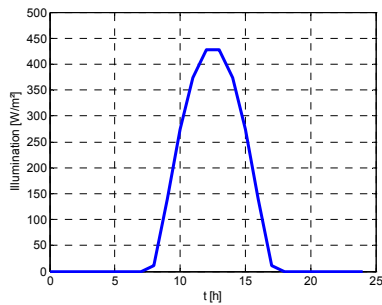


Fig. 4. Solar illumination profile.

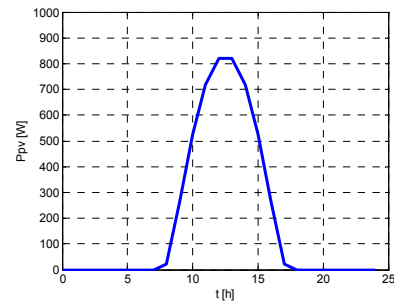


Fig. 5. Daily PV production.

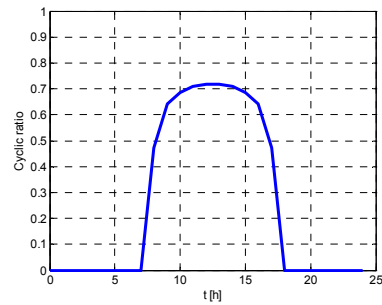


Fig. 6. Photovoltaic converter duty cycle changing.

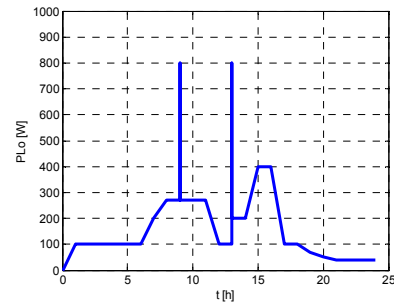


Fig. 7. Consumption profile.

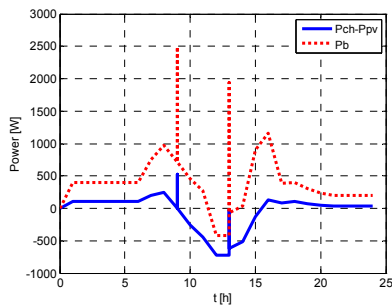


Fig. 8. Power curves.

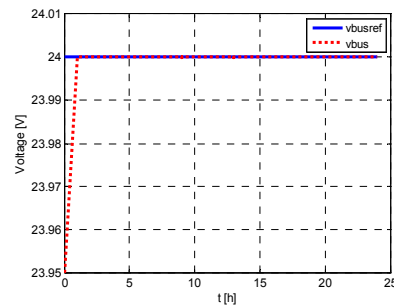


Fig. 9. DC link voltage and its reference.

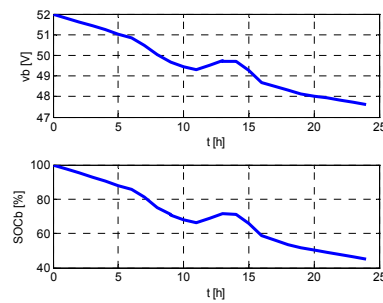


Fig. 10. Batteries voltage and state of charge.

In figures 9 and 10, and after a complete day of system operation, it is noted that the «charging/discharging» process of the lead-acid batteries is not respected because: $v_b < 47.2\text{V}$. The capacitive voltage v_{bus} is regulated to its reference.

3.5. Structure of the first autonomous hybrid system

Structure of the system "PV/Batteries/Supercapacitors" is showed in figure 11.

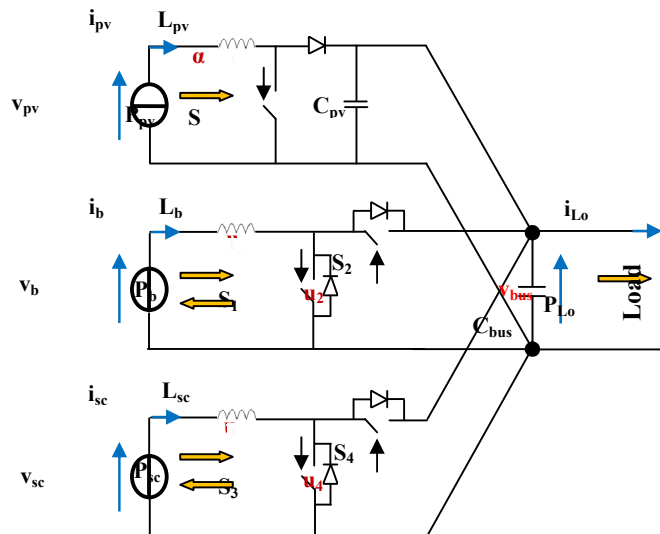


Figure 11. Structure of the second hybrid system.

Different characteristics of the added supercapacitors are summarized in Table 4.

Table 4. Characteristics of the supercapacitors.

Supercapacitors: BCAP0100 P270 T07 is chosen				
Maximal power [W]	Maximal voltage [V]	Elements number	Resistance [Ω]	Capacity [F]
2400	30	44	0.04125	36.36

The simulation results are shown in the next figures.

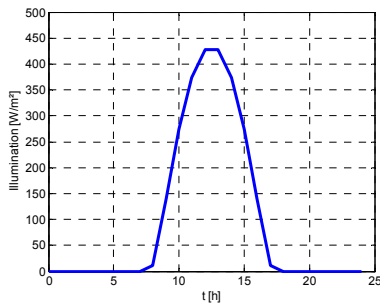


Fig. 12. Solar illumination profile.

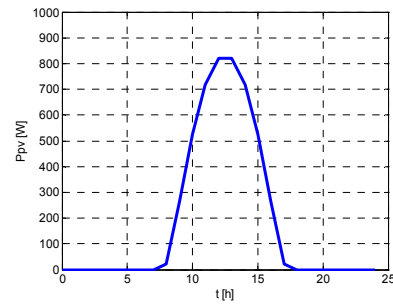


Fig. 13. Daily PV production.

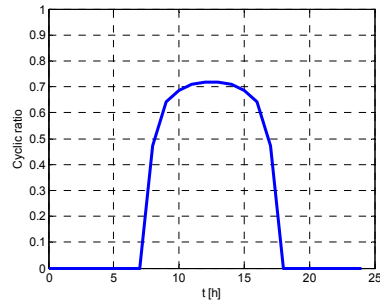


Fig. 14. Photovoltaic converter duty cycle changing.

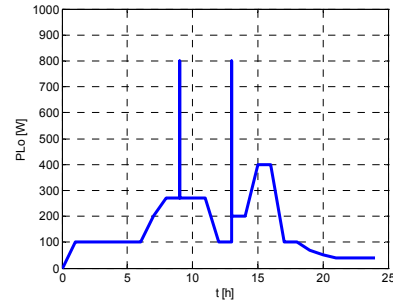


Fig. 15. Consumption profile.

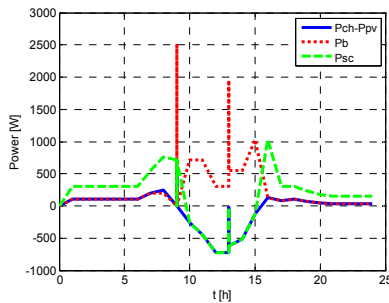


Fig. 16. Power curves.

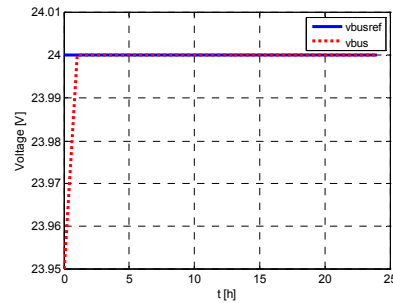


Fig. 17. DC link voltage and its reference.

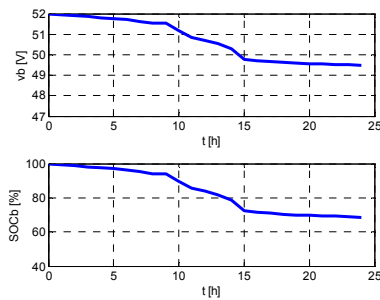


Fig. 18. Batteries voltage and state of charge.

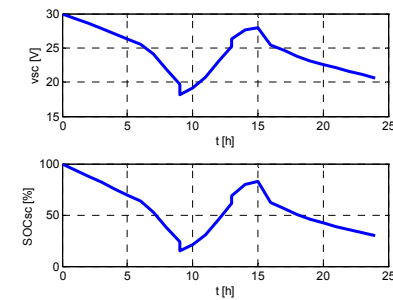


Fig. 19. Supercapacitors voltage and state of charge.

For this system, the "batteries/supercapacitors" hybrid source is considered as a storage unit. Using the same illumination and consumption profiles used for the previous system, and after a complete day of system operation, it is noted that the «charging/discharging» process of the lead-acid batteries and supercapacitors is respected as their states of charge are within admissible intervals since: $v_b \in [47.2, 52V]$ and $v_{sc} \in [15, 30V]$. The capacitive voltage v_{bus} is regulated to its reference. In fact:

- If the power $P_{ch}-P_{pv}$ available for charging the hybrid unit storage is less than batteries maximum power, batteries provide energy demand, and supercapacitors deliver two powers: one to compensate the difference between the consumer, PV source and batteries, and other needed to control v_{bus} . Therefore, voltages and states of charge are decreasing.
- When $P_{ch}-P_{pv}$ is positive and greater than batteries maximum power, batteries supply the difference between load and PV source, while supercapacitors deliver the necessary power to the capacitive voltage regulation. Thus, voltages and states of charge decrease.
- If $P_{ch}-P_{pv}$ is negative, it is absorbed by the supercapacitors (that have lower constant time), then by batteries (that have higher constant time). Figures 18 and 19 show that the excessive power produced by the PV source is always stored in supercapacitors which never reach the fully charge.

Fig. 20 indicates a comparison between the batteries state of charge for simple (in blue) and hybrid (in red) storages.

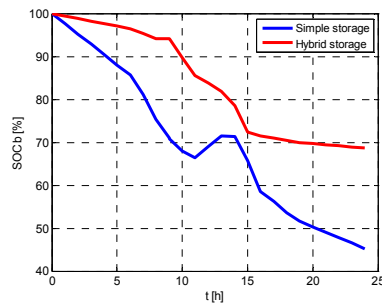


Fig. 20. Batteries state of charge for a simple and hybrid storages.

By applying a second profile (figure 21) obtained by dividing the daily power consumption by the half, evolution of the batteries state of charge is indicated in figure 22.

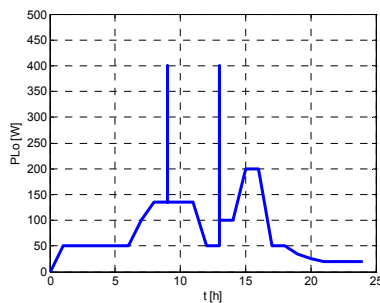


Fig. 21. Consumption profile.

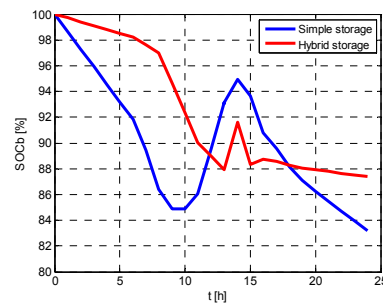


Fig. 22. Batteries state of charge for a simple and hybrid storages.

Table 5 shows that: more important is the discharge that lead-acid batteries received, more is the energy gain.

Table 5. Batteries final state of charge.

	Profile 1	Profile 2
Simple storage	45.26	83.21
Hybrid storage	68.66	87.42
ΔSOC_b [%]	23.40	04.21
Gain [Wh]	1101.6	198.2

Although supercapacitors are not an energy source, they bring to batteries a gain of 23.40% (Profile 1) in the final state of charge, which is equivalent to 1101.6Wh.

4. Conclusion

In this paper, the nonlinear flatness control was used to manage energy flows in two hybrid power systems: "PV/Batteries" and "PV/Batteries/Supercapacitors".

The simulation results have demonstrated that:

- The DC link voltage is controlled and regulated to its reference.
- The batteries and supercapacitors voltages and states of charge are maintained in their admissible intervals.
- Under conditions of high discharges, supercapacitors allow batteries to operate under reasonable conditions limiting strong solicitations and keeping them in a higher state of charge. Thus, the storage unit and hybrid sources lifetimes increase.

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